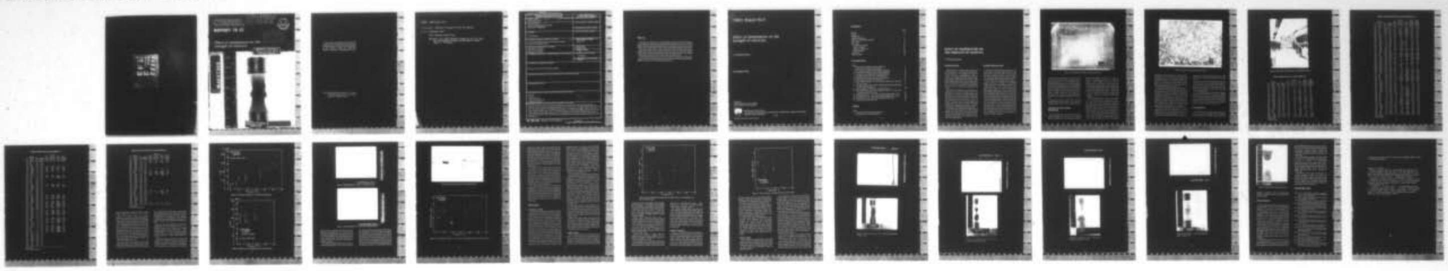
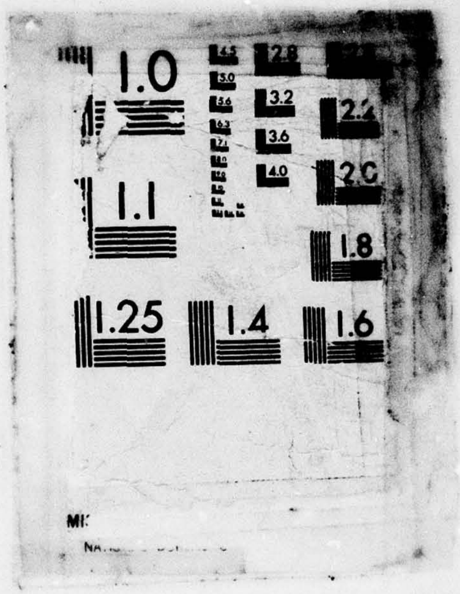
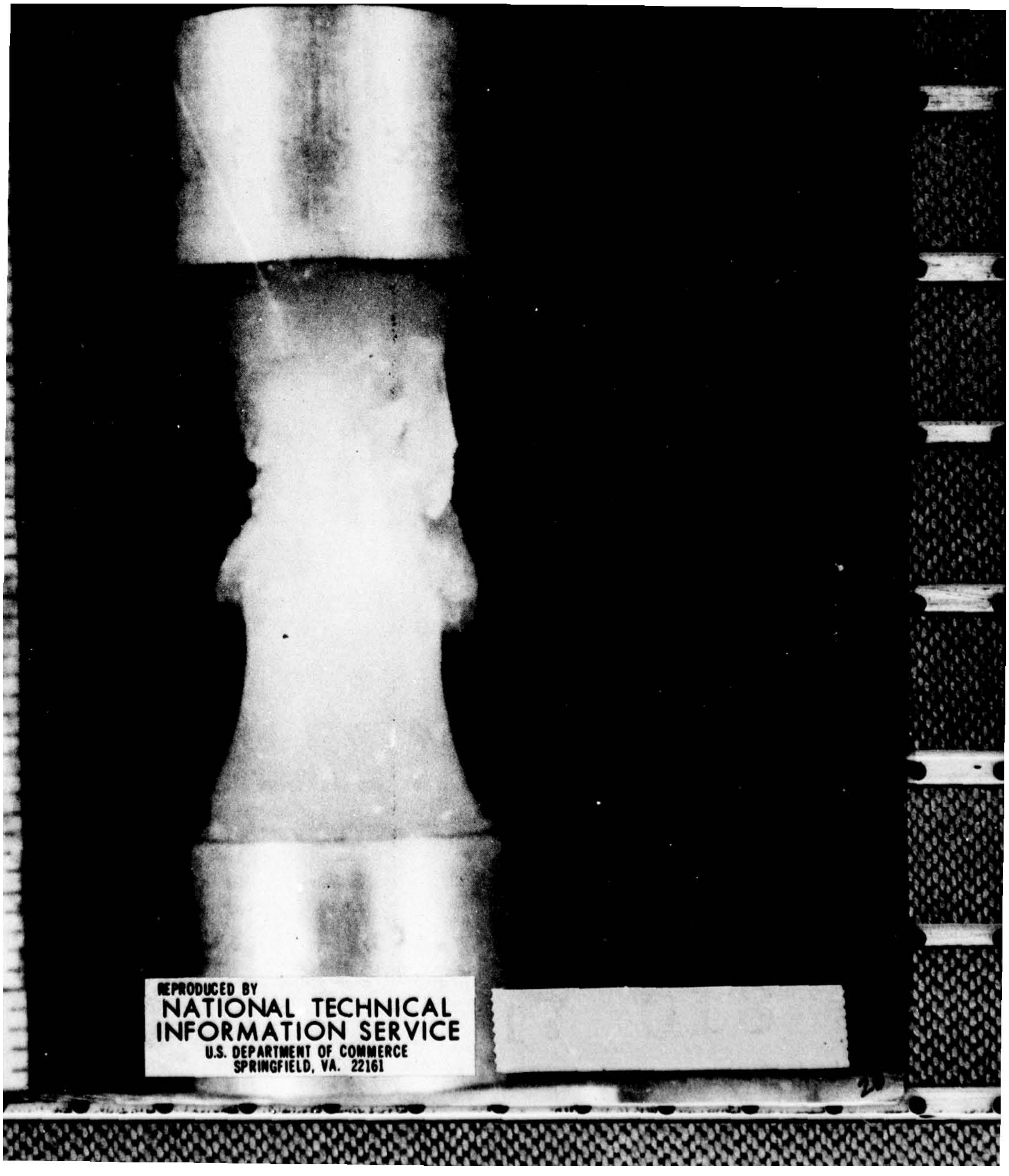
AD-A067 583 EFFECT OF TEMPERATURE ON THE STRENGTH OF SNOW-ICE(U) 1/1
COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH
F D HAYNES DEC 78 CRREL-78-27

UNCLASSIFIED F/G 8/12 NL



END
5_87
DTIC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Ductile failure of snow-ice at −0.1°C and a machine speed of 0.847 mm/s. (Photograph by F. Donald Haynes.)

ERRATA. CRREL Report 78-27

p. 11 and 12 - Captions of Figures 9 and 10 are reversed.

p. 18 - Literature Cited:

First reference should read:

Butkovich, T.R. (1954) Ultimate strength of ice. U.S. Snow, Ice and Permafrost Research Establishment Research Paper 11. AD 050514.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER CRREL Report 78-27	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EFFECT OF TEMPERATURE ON THE STRENGTH OF SNOW-ICE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) F. Donald Haynes		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31332
11. CONTROLLING OFFICE NAME AND ADDRESS Directorate of Civil Works Office, Chief of Engineers Washington, D.C. 02314		12. REPORT DATE December 1978 13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Snow-ice
Strain rate
Temperature effects
Uniaxial compression tests
Uniaxial tension tests

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Uniaxial compression and tension tests were conducted on polycrystalline snow-ice to determine the effect of temperature on its strength. Test temperatures ranged from −0.1°C to −54°C. Two machine speeds, 0.847 mm/s and 84.7 mm/s were used for the constant displacement rate tests. The compressive strength at −54°C was about one order of magnitude higher than at −0.1°C. The tensile strength at −18°C was about 20% higher than at −0.1°C. The initial tangent and 50% strength moduli are given for the compression tests, while the secant modulus to failure is given for the tension tests. The mode of fracture is discussed and the test results are compared with data from other investigations.

PREFACE

This report was prepared by F. Donald Haynes, Materials Research Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by Corps of Engineers Civil Works Project CWIS 31332, *Fundamental Mechanics of Ice Jams.*

The author would like to express gratitude to many technical personnel at CRREL for assistance with this project. Particular thanks are due to Dr. Donald Nevel and Dr. Malcolm Mellor for technically reviewing this report. Also making considerable contributions were John Ricard and John Kalafut.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

14

CRREL Report 78-27

6

Effect of temperature on the strength of snow-ice

10

F. Donald Haynes

11

December 1978

12 25p

Prepared for
DIRECTORATE OF CIVIL WORKS
OFFICE, CHIEF OF ENGINEERS
By

CRREL
DEPARTMENT OF THE ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY, CORPS OF ENGINEERS
HANOVER, NEW HAMPSHIRE

ii-a

Approved for public release; distribution unlimited.

037 100

CONTENTS

ILLUSTRATIONS

TABLES

EFFECT OF TEMPERATURE ON THE STRENGTH OF SNOW-ICE

F. Donald Haynes

INTRODUCTION

Polycrystalline ice made from saturated or compacted snow is commonly found on rivers, lakes and glaciers. The strength of freshwater snow-ice has been investigated by many researchers, including Butkovich (1955), Frankenstein (1959), Weeks and Assur (1969), Carter (1970), Hawkes and Mellor (1972) and Haynes (1973). A knowledge of the material properties of this type of ice is necessary for establishing design criteria for structures subjected to ice forces.

The present investigation was undertaken to determine the effect of temperature on the strength of ice loaded in uniaxial compression and tension. Two machine speeds, 0.847 mm/s and 84.7 mm/s, were used for the tests while the test temperature was varied from −0.1°C to −54°C. A load cell was used to determine the applied load and linear variable differential transformer transducers were used to measure deformation on dumbbell-shaped specimens.

In addition to the compressive and tensile test results, the initial tangent and 50% strength moduli were found for the compression tests, and the secant modulus was found for the tensile tests. These results were compared to those from other investigators.

SAMPLE PREPARATION

The snow-ice samples were prepared in a manner similar to that described by Hawkes and Mellor (1972) and Haynes (1973). The ice can be classified as bubbly, isotropic, polycrystalline ice. It was made by packing ice grains in a mold, saturating them with 0°C water and freezing.

The ice grains were obtained by disaggregating snow, passing it through a U.S. standard number 20 sieve and catching the grains on a number 40 sieve. A 12.7- × 27.4- × 7.4-cm split Lucite mold could form four 2.54-cm-diam × 8.26-cm-long samples at a time. Lucite inserts were placed in the cylinders of the mold to produce dumbbell-shaped specimens. Aluminum end caps were placed in the mold and frozen onto the specimens during the freezing stage. The snow was compacted at −10°C by slowly adding snow to the four holes of the mold while it was on a vibrator. A 1.27-cm-diam plastic tube was attached to a brass adapter threaded into the bottom end cap of each cylinder. Distilled, degassed water at 0°C was then added to each hole. This method forced some of the air out of the compacted snow but many bubbles remained as shown in Figure 1.

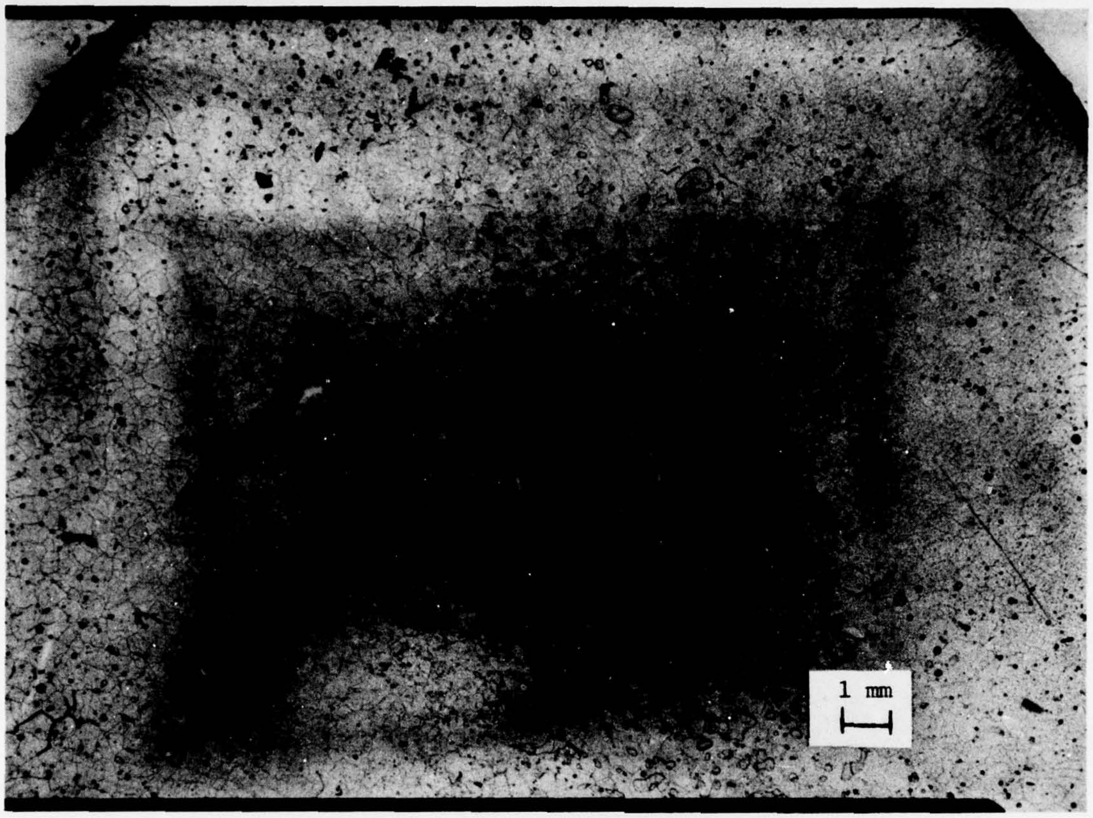


Figure 1. Distribution of bubbles in polycrystalline ice.

Insulation was then placed on the top and sides of the mold, and it was placed in an ambient temperature of −23°C for freezing. Directional freezing took place from the base upward, which minimized freezing strains and entrapped water. The ice had a bulk density of 0.911 Mg/m^3 and the average bubble size was about 0.2 mm (Fig. 1). Freezing at a low temperature tended to reduce bubble migration and produce a specimen with a more uniform bubble distribution. The outer periphery tended to be bubble-free.

The grain structure is shown in Figure 2. Under polarized light the grains appear to be randomly oriented with an average size of about 0.6 mm.

APPARATUS AND TESTING PROCEDURE

All ice samples were tested on an MTS closed-loop electrohydraulic testing machine, Model 907.52, equipped with a temperature-controlled Bemco environmental chamber, as shown in Figure 3. Two thermocouples, one mounted adjacent to the sample to monitor the air temperature in the chamber and the other attached to the bottom platen, were connected to a Fluke 2100A digital thermometer and provided a continuous temperature check. A heat sink device was used for the tests run at −0.1°C and −3°C. It consisted of metal cans filled with crushed ice and placed around the sample in the chamber.

Since the samples were stored in a coldroom at −7°C and tested over a range from −0.1°C to −54°C, sufficient time had to be allowed for the samples to reach an equilibrium state with the desired test temperature of the chamber. A dummy sample, wired with three thermocouples, was used to determine that a minimum conditioning time of 1½ hours was required for a test at −54°C, while the conditioning times for tests at other temperatures usually did not exceed 1 hour. A special equilibration procedure was used for the tests at −0.1°C. The samples

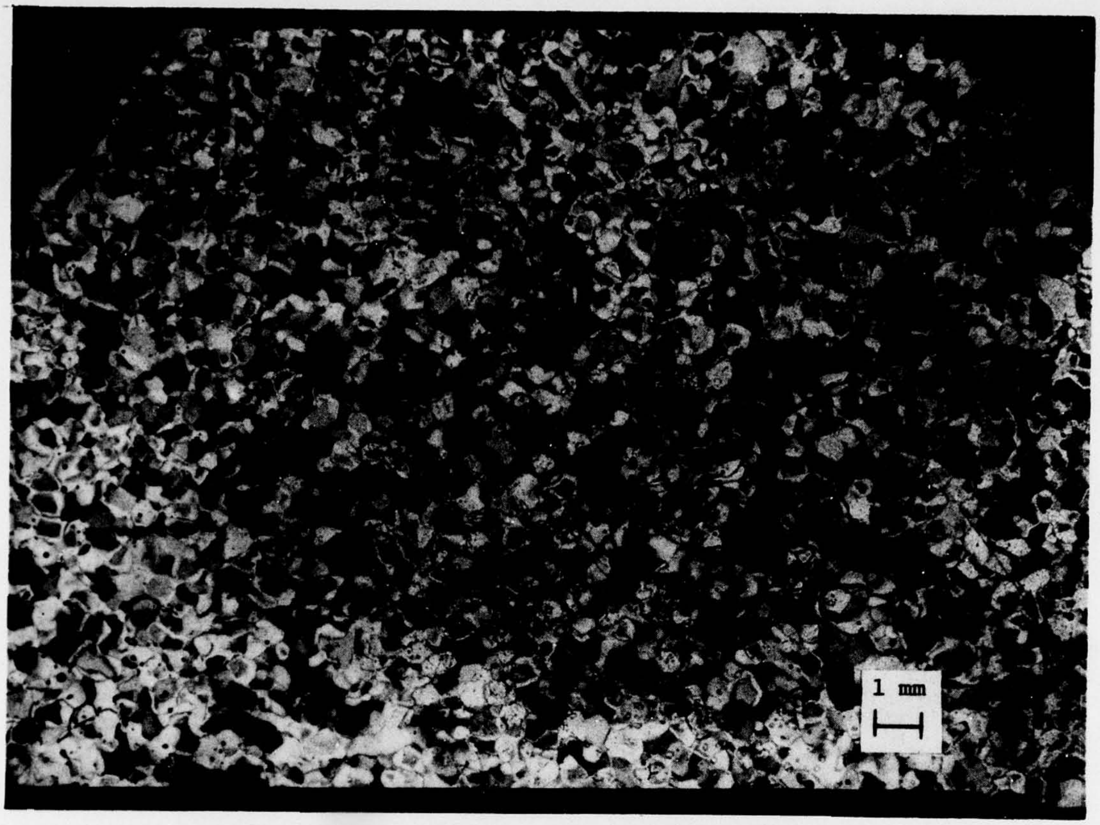


Figure 2. Grain structure under polarized light.

were placed in the chamber at −0.5°C and conditioned for ½ hour. The chamber temperature was then raised to −0.1°C and the sample conditioned for at least 15 minutes before the test was run. According to transient heat transfer theory, this was greater than the time required for central temperature equilibration.

Fluctuations of the temperature inside the environmental chamber and those caused by opening and closing of the chamber door were observed. The chamber normally cycled through a change of about ±0.1°C every minute, but short-term fluctuations, e.g. about 5°C in 30 seconds, occurred when the chamber door was opened and then closed. The ice-filled metal cans absorbed heat introduced when the door was opened and helped to stabilize the temperature and decrease the fluctuations.

In most of the compression tests, a 25-tonne capacity load cell, MTS Model 661.22, with an accuracy of ±2% of the measured value, was used to determine the applied load. For lower expected loads at higher temperatures and slower loading rates, and for all the tensile tests, a 909-kg Baldwin-Lima-Hamilton SR-4 load cell was used.

Two linear variable differential transformer (LVDT) transducers were used to measure the axial deformation of the samples. They were attached to the sample end caps 180° apart, and their output signals were averaged to obtain the average displacement.

Load and displacement curves were recorded on a Tektronix dual-beam oscilloscope, Model R5103N. Load and time curves were recorded on a Tektronix 502A dual-beam oscilloscope and a Biomation 802 transient recorder. The transient recorder was used to store data since the fastest test had a time to failure of about 5 ms.

TEST RESULTS

Data for the uniaxial compression and tension tests are presented in Tables I and II. A total of 78 compression tests and 85 tension tests were

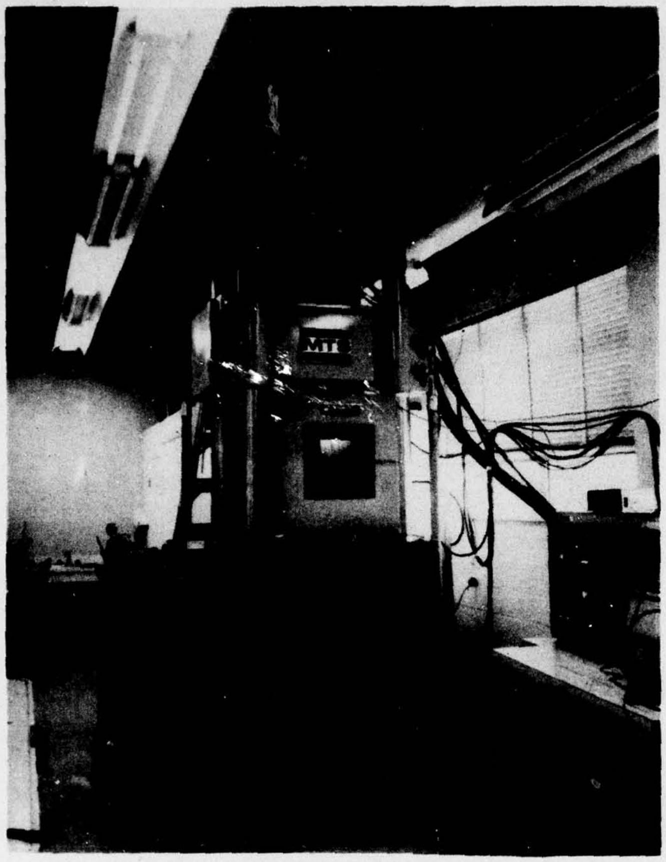


Figure 3. MTS machine and Bemco environmental chamber.

Table I. Compression tests of polycrystalline ice.

Test no.	Machine speed (mm/s)	Temp (°C)	Strength (MN/m²)	Failure strain ($\times 10^{-4}$)	Avg strain rate to peak stress (10^{-3} s^{-1})	Time to failure (s)	Initial tangent modulus (GN/m²)	50% strength modulus (GN/m²)
I1C	0.847	− 7.0	10.89	M*	M	M	M	M
I2C	0.847	− 7.0	7.02	M	M	M	M	M
I3C	0.847	− 7.0	10.3	7.0	1.98	0.353	14.8	14.8
I4C	0.847	− 7.0	10.09	7.0	1.98	0.353	14.4	14.4
I5C	0.847	− 7.0	10.18	9.0	2.5	0.348	11.3	11.3
I6C†	0.847	− 7.0	7.67	M	M	M	M	M
I7C	0.847	− 7.0	8.6	7.0	1.7	0.41	12.47	12.47
I8C	0.847	−17.8	10.09	8.73	1.86	0.469	11.57	11.57
I9C	0.847	−17.8	12.29	10.5	1.82	0.576	8.19	8.19
I10C	0.847	−17.8	13.7	10.5	1.85	0.566	13.05	13.05
I11C	0.847	−17.8	10.71	6.98	1.50	0.465	15.34	15.34
I12C	0.847	−34.5	20.19	13.1	M	M	15.4	15.4
I13C	0.847	−34.5	28.9	21.8	M	M	13.26	13.26
I14C	0.847	−34.5	29.4	26.0	M	M	11.31	11.31
I15C	0.847	−34.5	25.02	13.0	1.79	0.732	19.12	19.12
I16C	84.7	−34.5	17.6	M	M	0.024	M	M
I17C	84.7	−34.5	21.5	M	M	0.024	M	M
I18C	84.7	−34.5	28.53	40.0	M	M	7.11	7.11
I19C	0.847	−43.7	32.48	41.0	4.67	0.879	7.92	7.92
I20C	0.847	−40.0	32.04	23.6	2.68	0.879	16.77	15.48

*Data missing
†Flaw in specimen

Table I (cont'd). Compression tests of polycrystalline ice.

Test no.	Machine speed (mm/s)	Temp (°C)	Strength (MN/m²)	Failure strain (× 10⁻⁴)	Avg strain rate to peak stress (10⁻³ s⁻¹)	Time to failure (s)	Initial tangent modulus (GN/m²)	50% strength modulus (GN/m²)
121C	0.847	−40.0	28.53	17.5	2.23	0.781	25.16	14.38
122C	84.7	−42.0	35.1	25.3	143.94	0.018	20.13	14.38
123C	84.7	−50.0	38.63	M	M	0.0195	M	M
124C	84.7	−51.0	34.24	19.0	109.06	0.0176	18.02	18.02
125C	84.7	−49.0	41.7	31.4	189.21	0.0166	25.16	14.38
126C	0.847	− 0.1	4.83	10.5	3.77	0.278	5.03	3.59
127C	0.847	− 0.1	4.61	11.34	2.90	0.391	12.55	12.55
128C	84.7	− 0.1	7.46	6.1	M	M	16.73	16.73
129C	0.847	− 3.0	1.98	M	M	M	M	M
130C	0.847	− 3.0	8.87	9.6	1.745	0.55	9.24	9.24
131C	0.847	− 3.0	9.44	11.3	1.890	0.60	8.35	8.35
132C	0.847	− 3.0	14.75	15.7	2.094	0.75	8.05	8.05
133C	0.847	− 3.0	12.99	14.8	3.296	0.45	10.09	8.07
133C	0.847	−10.0	15.3	M	M	M	M	M
135C	0.847	−10.0	19.3	13.38	2.027	0.66	10.06	10.06
136C	0.847	−10.0	20.2	12.8	1.933	0.662	12.58	12.58
137C	0.847	−10.0	10.97	M	M	M	M	M
138C	0.847	−10.0	16.68	11.6	2.06	0.564	12.58	12.58
139C	84.7	−10.0	15.10	11.3	82.79	0.0137	16.77	12.58
140C	84.7	−10.0	15.80	13.1	140.73	0.0093	12.58	12.58
141C	0.847	−35.0	34.46	30.5	M	M	12.58	8.38
142C	0.847	−35.0	18.44	22.7	3.32	0.684	10.06	10.06
143C†	0.847	−35.0	15.36	M	M	M	M	M
144C	0.847	−36.0	27.21	21.8	M	M	12.58	12.58
145C	0.847	−35.0	23.45	21.8	3.45	0.633	12.58	12.58
146C	0.847	−53.0	M	M	0.977	M	M	
147C†	0.847	−52.0	8.78	M	M	M	M	M
148C†	0.847	−48.3	17.55	M	M	M	M	M
149C	0.847	−47.0	37.75	28.8	3.257	0.884	13.97	13.97
150C	0.847	−45.8	29.85	26.2	3.15	0.830	11.18	11.18
151C	0.847	− 0.1	5.27	3.5	1.89	0.186	15.06	15.06
152C	84.7	−54.0	36.21	M	M	0.0195	M	M
153C	84.7	−54.0	43.89	21.0	119.94	0.0176	19.96	19.96
154C	84.7	−54.0	53.11	31.7	162.38	0.0195	14.26	14.26
155C	84.7	−53.0	57.50	33.4	171.40	0.0195	16.64	16.64
156C	84.7	−53.0	50.04	29.9	160.78	0.0186	14.26	14.26
157C	0.847	−19.0	6.14	M	M	M	M	M
158C	0.847	−19.0	13.17	24.6	M	M	7.13	7.13
159C	0.847	−19.0	14.92	26.4	M	M	5.54	5.54
160C	0.847	−19.0	14.05	26.4	M	M	5.54	5.54
161C	0.847	−19.0	23.70	48.9	6.06	0.806	5.59	5.59
162C	0.847	−19.0	21.29	43.6	4.47	0.977	5.59	5.59
163C	0.847	−19.0	20.63	48.0	5.17	0.928	4.57	4.57
164C	84.7	− 3.0	8.78	6.98	7.12	0.0098	12.58	12.58
165C	84.7	− 3.0	8.47	6.98	8.95	0.0078	11.21	11.21
166C	84.7	− 3.0	8.56	4.8	61.52	0.0078	8.07	8.07
167C	84.7	− 0.1	6.94	6.1	96.94	0.0063	10.09	10.09
168C	84.7	− 0.1	5.05	3.49	M	M	14.47	14.47
169C	84.7	− 0.1	5.05	6.1	124.64	0.0049	8.28	8.28
170C	84.7	−18.5	20.85	34.9	298.29	0.0117	5.59	5.59
171C	84.7	−18.5	21.07	41.9	427.35	0.0098	2.02	2.02
172C	84.7	−18.5	17.78	57.6	394.42	0.0146	5.30	5.30
173C	0.847	−18.5	16.68	30.5	4.12	0.742	5.59	5.59
174C†	0.847	−17.5	10.10	35.8	6.10	0.586	2.82	2.82
175C	0.847	−17.5	15.36	33.2	5.44	0.609	5.03	5.03
176C	84.7	−17.5	20.63	32.8	M	M	11.00	5.82
177C	84.7	−17.5	18.44	39.9	407.15	0.0098	11.00	5.50
178C	0.847	− 2.0	8.34	17.5	4.30	0.406	5.75	3.94

*Data missing
†Flaw in specimen

Table II. Tension tests of polycrystalline ice.

Test no.	Machine speed (mm/s)	Temp (°C)	Strength (MN/m²)	Failure strain (× 10⁻⁴)	Avg strain rate to peak stress (10⁻³ s⁻¹)	Time to failure (s)	Secant modulus (GN/m²)
I1T	84.7	− 3.0	1.32				
I2T	84.7	− 3.0	1.49				
I3T	84.7	− 3.0	1.05				
I4T	0.847	− 3.0	1.83	2.18	0.283	0.771	8.39
I5T	0.847	− 3.0	2.32	3.40	3.24	1.05	6.82
I6T	0.847	− 3.0	2.90	3.40	0.193	1.76	8.53
I7T	0.847	− 7.0	1.84	3.49	M*	M	M
I8T	0.847	− 7.0	1.36				
I9T	0.847	− 7.0	1.63				
I10T	0.847	− 7.0	1.84	3.49	0.750	0.465	5.27
I11T	84.7	− 7.0	1.45	3.05	31.23	0.0098	4.75
I12T	84.7	− 7.0	1.49				
I13T	84.7	−18.0	1.14				
I14T	84.7	−18.0	1.63				
I15T	83.7	−18.0	1.63				
I16T	0.847	−18.0	2.37	5.24	0.865	0.605	4.52
I17T	0.847	−18.0	2.11	6.11	0.973	0.625	4.52
I18T	0.847	−18.0	1.67				
I19T	0.847	−18.0	2.11				
I20T	84.7	−18.0	1.93				
I21T	84.7	−18.0	1.84				
I22T	84.7	−18.0	1.32				
I23T	0.847	−18.0	2.81	4.36	0.616	0.708	6.44
I24T	0.847	−18.0	2.19	5.45	0.915	0.596	4.02
I25T	0.847	−18.0	2.72	6.54	0.842	0.777	4.16
I26T	0.847	−18.0	1.84				
I27T	0.847	−18.0	2.19	5.45	0.901	0.605	4.02
I28T	0.847	−18.0	3.15	6.54	0.877	0.746	4.81
I29T	84.7	−18.0	2.02	3.27	33.5	0.0098	6.18
I30T	84.7	−18.0	1.93	4.36	40.6	0.0107	4.42
I31T	0.847	−18.0	2.02	5.45	0.955	0.571	3.71
I32T	0.847	−18.0	1.62				
I33T	0.847	− 7.0	1.93	6.54	0.684	0.957	3.95
I34T	0.847	− 1.5	1.80	3.45	0.668	0.522	5.16
I35T	0.847	− 1.5	2.02	4.36	0.687	0.635	5.63
I36T	84.7	− 1.1	1.71	3.93	M	M	M
I37T	0.847	−18.2	1.71				
I38T	0.847	− 1.4	1.71	2.18	0.430	0.508	7.84
I39T	84.7	− 1.3	2.11	3.05	15.66	0.0195	6.92
I40T	84.7	− 1.1	2.37	3.05	31.3	0.0098	7.77
I41T	0.847	− 0.1	2.11	3.93	0.745	0.527	5.37
I42T	0.847	− 0.1	0.79				
I43T	0.847	− 0.1	2.28	3.49	0.60	0.581	6.53
I44T	84.7	− 0.1	1.93	3.49	51.32	0.0068	5.53
I45T	84.7	− 0.1	2.11	3.49	35.61	0.0098	6.05
I46T	84.7	− 0.1	1.89	3.49	35.61	0.0098	5.42
I47T	84.7	− 5.7	2.19	3.05	31.16	0.0098	7.18
I48T	0.847	−18.0	1.58				
I49T	0.847	−18.0	1.76				
I50T	0.847	−18.0	1.71				
I51T	0.847	−18.0	1.71				
I52T	0.847	−53.0	1.40				
I53T	0.847	−50.0	1.32				
I54T	0.847	−52.0	1.58				
I55T	84.7	−51.0	1.32				
I56T	0.847	−51.0	1.71				

*Data missing

No entry means invalid test.

Table II (cont'd). Tension tests of polycrystalline ice.

Test no.	Machine speed (mm/s)	Temp (°C)	Strength (MN/m²)	Failure strain (× 10⁻⁴)	Avg strain rate to peak stress (10⁻³ s⁻¹)	Time to failure (s)	Secant modulus (GN/m²)
157T	0.847	− 9.5	1.73	4.90	M*	M	3.53
158T	0.847	− 9.2	1.73	4.90	1.02	0.480	3.53
159T	0.847	− 9.6	1.32				
160T	0.847	− 9.6	1.05				
161T	0.847	−21.0	1.27				
162T	0.847	−21.0	2.24	M	M	M	M
163T	0.847	−21.0	1.45				
164T	84.7	− 9.7	2.28	4.90	50.02	0.0098	4.65
165T	84.7	− 9.7	1.84	4.66	63.79	0.0073	3.95
166T	0.847	−18.5	2.19	8.58	1.56	0.5508	2.55
167T	0.847	−18.5	1.32				
168T	0.847	−10.0	1.58				
169T	0.847	−12.0	1.54				
170T	0.847	−18.5	0.83				
171T	0.847	−18.5	1.58				
172T	0.847	−36.5	1.54				
173T	0.847	−36.5	1.45				
174T	0.847	−36.5	1.14				
175T	0.847	−36.5	1.23				
176T	84.7	−36.5	1.54				
177T	84.7	−36.5	2.50	5.00	6.4	0.078	5.00
178T	84.7	−36.5	2.90	M	M	0.0645	M
179T	84.7	−51.0	0.99				
180T	84.7	−51.0	1.23				
181T	0.847	−51.0	1.80				
182T	0.847	−51.0	1.62				
183T	0.847	−52.0	1.58				
184T	84.7	−52.0	1.14				
185T	0.847	−18.0	2.37	4.36	M	M	5.43

*Data missing.

No entry means invalid test.

made. Temperature was the principal variable and tests were run at −0.1°, −3°, −7°, −10°, −18°, −35° and −54°C. The lowest temperature could not be steadily maintained at times, so that some tests had to be run at higher temperatures. The test machine was operated in a constant displacement mode for all tests. Two rates of loading were used, 0.847 mm/s and 84.7 mm/s, representing a slow and a fast test. The failure stress was easily determined from each load-deformation curve. An analysis was done by Haynes et al. (1975) to determine the strain in the neck section of the dumbbell specimen. A factor of 0.349 ΔL, where ΔL is the deformation measured by the LVDT's between end caps, was used for calculating the strain.

At least three tests were run at each temperature and at each machine speed in both tension and compression. More than half of the samples broke at the end caps in the tension tests, although the desired plane of failure for the tension tests was in the neck section of the dumbbell-shaped specimen. Therefore, at each combination of temperature and machine speed, an attempt was made to run tension tests until at least one sample failed in the neck section.

Figure 4 shows the strength as a function of temperature for the compression tests. At a machine speed of 84.7 mm/s, the average strength increased from 5.85 MN/m² at −0.1°C to 48.15 MN/m² at −54°C. At a machine speed of 0.847 mm/s, the average strength increased from 4.9 MN/m² at −0.1°C to 40.12 MN/m² at −53°C.

The relationship between tensile strength and temperature is shown in Figure 5. The tensile strength is relatively insensitive to temperature and lies between 1.71 MN/m² and 3.16 MN/m² over the range of test temperatures. More than

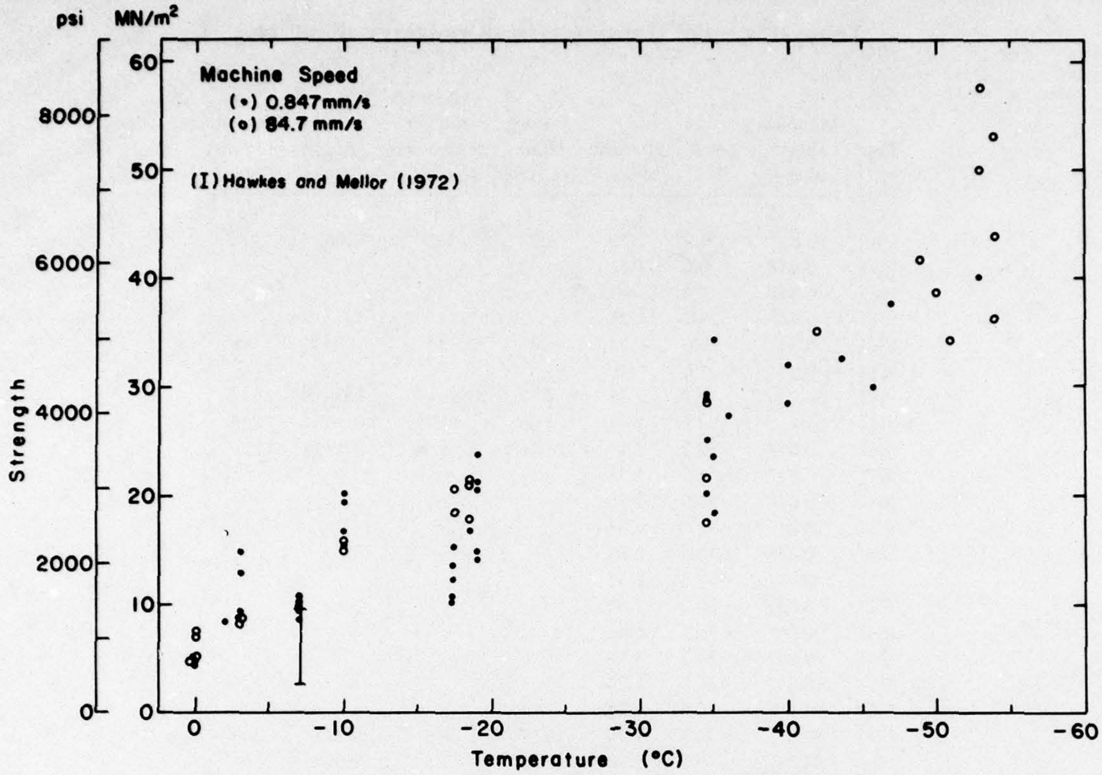


Figure 4. Compressive strength as a function of temperature.

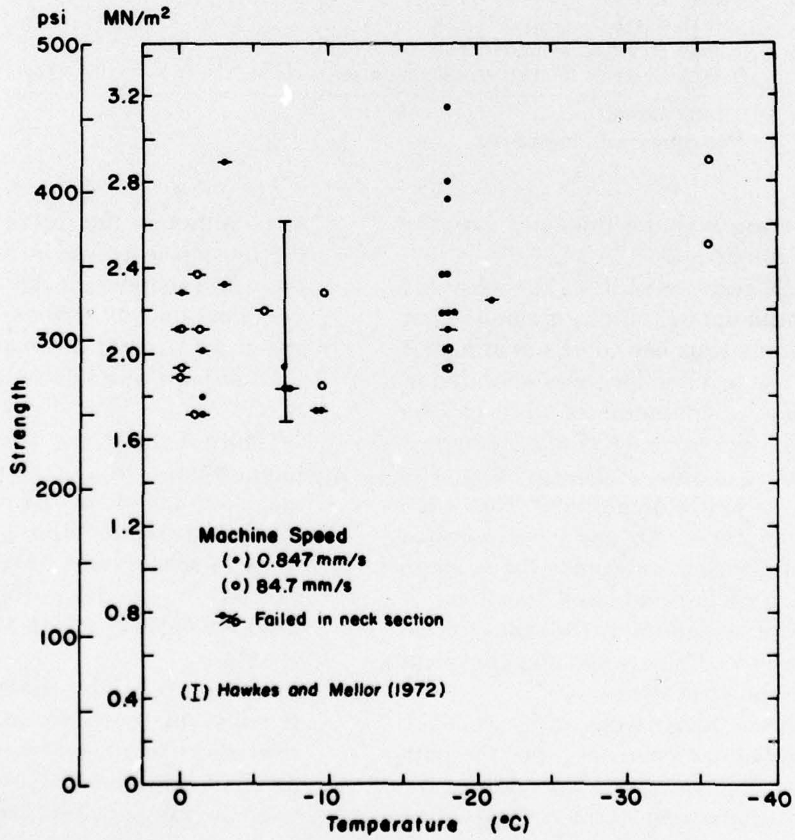


Figure 5. Strength of ice vs temperature for the tension tests.

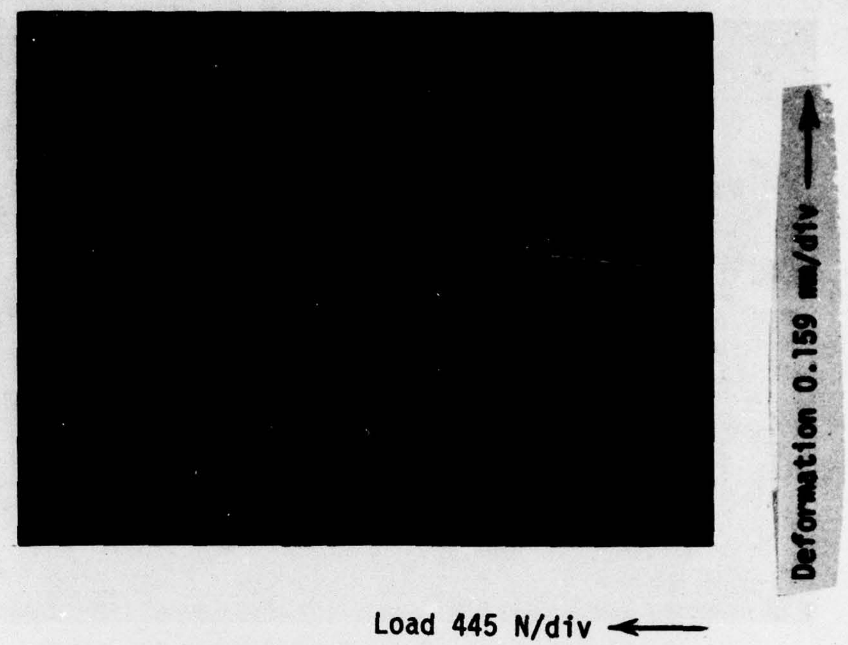


Figure 6. Load-deformation curve for a valid tensile test.

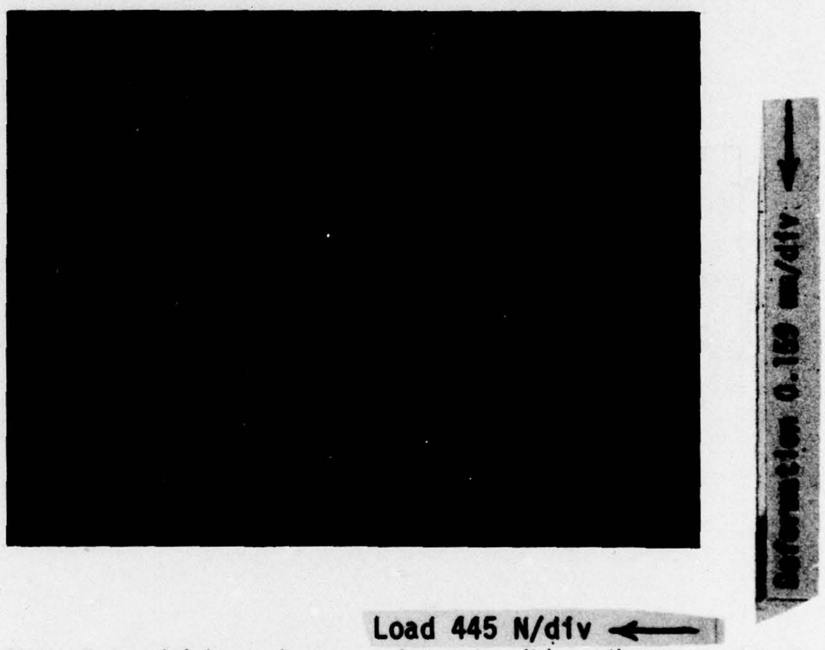


Figure 7. Load-deformation curve for an invalid tensile test.

half of the tests reported in Table II are considered to be invalid tests. The criterion for this invalidity is slippage of the specimen in the end cap as determined from the load-deformation curve. Figure 6 shows a valid test while Figure 7 shows an invalid test. Only the valid tests are plotted in Figure 5.

The specimen tended to fail in the neck section for tests down to −7°C, the test temperature used by Hawkes and Mellor (1972). Below this temperature it was very difficult to obtain specimen failure in the neck section. One reason for specimen failure at the end cap was that unequal thermal contraction between the ice and aluminum end cap produced strains in the ice prior to testing. An attempt was made to prevent the effects of unequal thermal expansion by attaching split end caps to the specimen after the

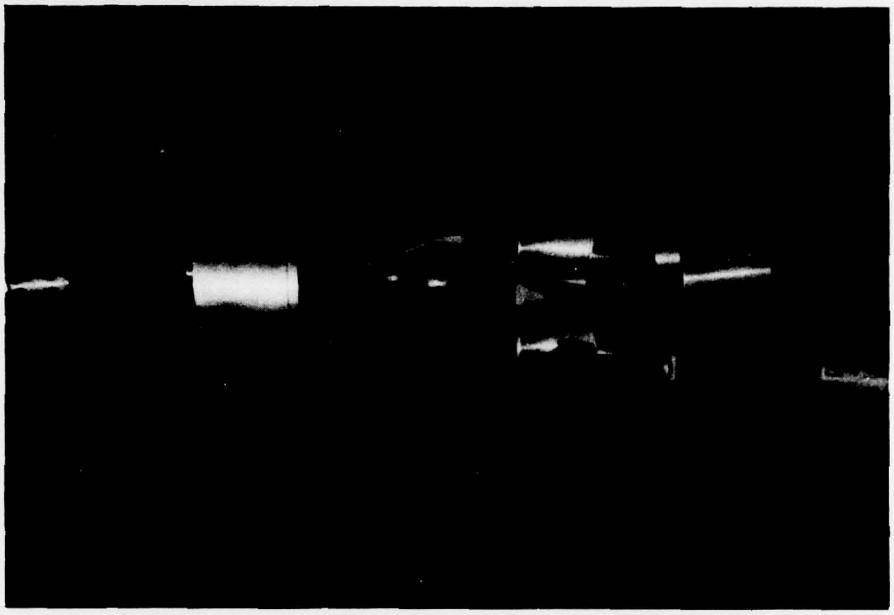


Figure 8. Split end caps used for some tensile tests.

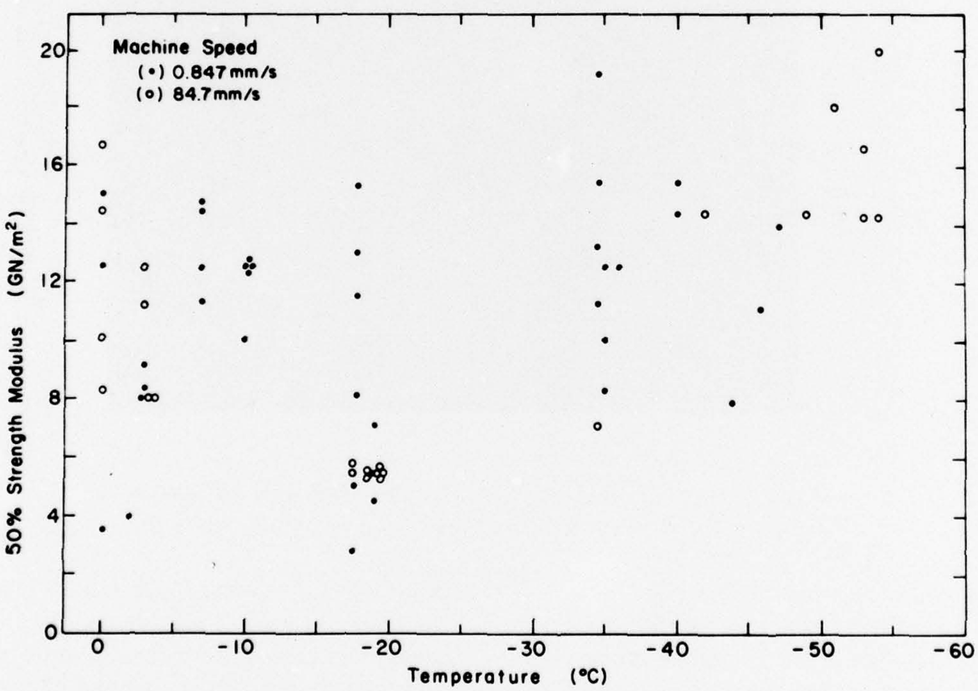


Figure 9. Initial tangent modulus as a function of temperature for the compression tests.

specimen was made. Figure 8 shows the split end caps used. Similar split caps were used by Dykins (1966) for tensile tests on sea ice. The results of using the split caps in this investigation were only moderately successful; i.e. most of the specimens still failed at the end cap. However, the only specimens which did fail in the neck section below $-10°C$ are those in which the split caps were used. A better design is required in order to conduct reliable tensile tests at low temperatures.

The calculation of failure stress for each test was based on the cross-sectional area of the neck section of the sample. The rationale for plotting many tests whose failure occurred at the end cap, as well as those that failed at the neck section, is that the minimum area sustained the failure load even though it was not always in the failure plane. The points plotted in Figure 5 therefore represent the minimum failure stress for the range of test temperatures.

The initial tangent modulus as a function of temperature is shown in Figure 9. The relationship between the modulus at 50% strength and temperature is shown in Figure 10. Both figures indicate that the modulus tends to increase with decreasing temperature for the compression tests. Figure 11 shows the secant modulus to failure for the tensile tests as a function of temperature.

DISCUSSION

Compressive strength

The uniaxial compressive strength of natural and artificial ice has been the topic of many investigations. Many of these tests were performed on relatively soft machines that could have influenced the results considerably. Butkovich (1954) tested snow-ice and clear ice from a lake over a temperature range from 0°C to $-50°C$, and found that the maximum strength increased from 2.67 MN/m^2 to 5.6 MN/m^2 for the snow-ice and from 2.52 MN/m^2 to 9.71 MN/m^2 for the clear ice. He also noted a rate of increase of 0.018 MN/m^2 °C for snow-ice and 0.07 MN/m^2 °C for lake ice at unreported strain rates. Wolfe and Thieme (1964) report an increase in strength from 1.86 MN/m^2 to 5.34 MN/m^2 for river ice and from 3.28 MN/m^2 to 6.55 MN/m^2 for laboratory grown ice over a temperature range from $-10°C$ to $-60°C$. They found a rate of about 0.08 MN/m^2 °C for river ice and 0.15 MN/m^2 °C for laboratory grown ice. Mellor and Smith (1966) tested snow-ice at temperatures from 0°C to $-50°C$. The average strength increased from 1.67 MN/m^2 at 0°C to 3.82 MN/m^2 at $-50°C$. They found a maximum rate of about 0.2 MN/m^2 °C for the bubbly ice. The effect of temperature on the strength of ice is discussed by Weeks and Assur (1969). Kovacs et al. (1977) conducted uniaxial compression tests on snow (6.01–6.24-Mg/m^3 density) from Greenland. They report a maximum stress of 3.27 MN/m^2 at $-21°C$. They also discuss a rate of strength increase with temperature for snow-ice found by other investigators. The average rate between $-20°C$ to $-40°C$ was 0.076 MN/m^2 °C.

The compressive strength found in this study is considerably higher than reported by other investigators for comparable temperatures and loading rates. Figure 4 shows that the average strength increased from 4.9 MN/m^2 at $-0.1°C$ to 40.12 MN/m^2 at $-53°C$ for the tests run at a machine speed of 0.847 mm/s. For the machine speed of 8.47 mm/s the average strength increased from 6.13 MN/m^2 at $-0.1°C$ to 48.15 MN/m^2 at $-54°C$. The maximum strength values for the 0.847-mm/s machine speed showed a rapid increase from $-0.1°C$ to $-3°C$ which may be the result of interstitial unfrozen water. However, between $-3°C$ and $-35°C$ the rate of increase was 0.6 MN/m^2 °C. At the machine speed of 8.47 cm/s the average strength increased at a rate of 0.78 MN/m^2 °C.

In this study all tests were conducted on a relatively stiff machine. This machine prevents, to a high degree, energy stored in the system from causing specimen failure once cracks are initiated. It is this characteristic of the testing machine which probably accounts for the higher strength values.

Hawkes and Mellor (1972) showed that the compressive strength of snow-ice increases with strain rate. At $-7°C$ the present results agree with Hawkes and Mellor, since the higher strain rates produced higher strengths. However, the strain rate effect is not conclusive since there is considerable scatter (see Fig. 4).

Tensile strength

Precise, valid tensile tests are difficult to perform. To consistently obtain specimen failure in the neck section without any flexural stresses or slippage of the gripping system is a challenge. Hawkes and Mellor (1972) conducted uniaxial tensile tests on polycrystalline snow-ice similar

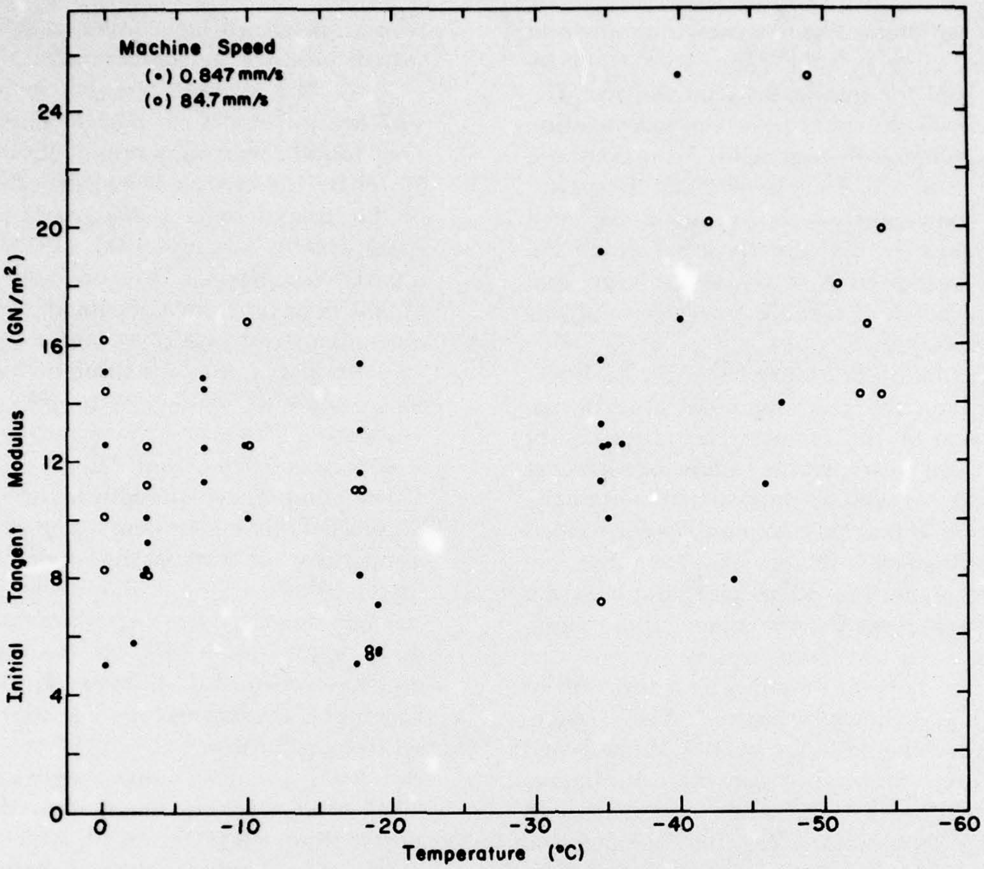


Figure 10. The relationship between 50% strength modulus and temperature for the compression tests.

to that tested in this investigation. The strengths that they found at $-7°C$ (shown in Fig. 5) ranged from 1.68 MN/m² to 2.62 MN/m². They found the strength to be relatively insensitive to strain rate in the range from 10^{-7} to 10^{-2} s^{-1}. They also discuss the different gripping systems used by other investigators including Butkovich (1954) and Dykins (1966).

Dykins (1966) conducted tensile tests on laboratory grown sea ice. For specimens cored in a vertical direction, the mean strengths ranged from 1.05 MN/m² at $-10°C$ to 1.43 MN/m² at $-27°C$, indicating a temperature effect for sea ice in this range. (The strength of sea ice is typically lower than that of freshwater ice.) Dykins employed split end caps similar to the ones used in this study.

Carter (1970) reports a slight effect of temperature on the tensile strength of ice. His maximum strengths ranged from 2.11 MN/m² at 0°C to 2.26 MN/m² at $-30°C$.

It was found in this study that valid tensile tests were difficult to obtain. Figure 5 shows that specimen failure in the neck section was usually obtained for temperatures above $-10°C$. However, at $-18°C$ and $-36°C$ the specimens seldom failed in the neck section.

The tensile strengths agree very well with those obtained by Hawkes and Mellor (1972) at $-7°C$. At lower temperatures the strengths are higher, indicating a temperature effect. The maximum strengths for the 0.847-mm/s tests suggest a rapid increase between $-0.1°C$ and $-3°C$, which may be the result of interstitial unfrozen water. The tensile strength shows some agreement with Carter (1970) at $-0.1°C$ but tends to be much higher than Carter's results at lower temperatures.

Modulus of elasticity

There is not much information available on the modulus of elasticity for ice since accurate values for specimen deformation are difficult to obtain. Hawkes and Mellor (1972), however, report values for the initial tangent modulus for ice. At $-7°C$ they found this modulus to be insensitive to strain rate for compression tests and found that it increased slightly for tension tests

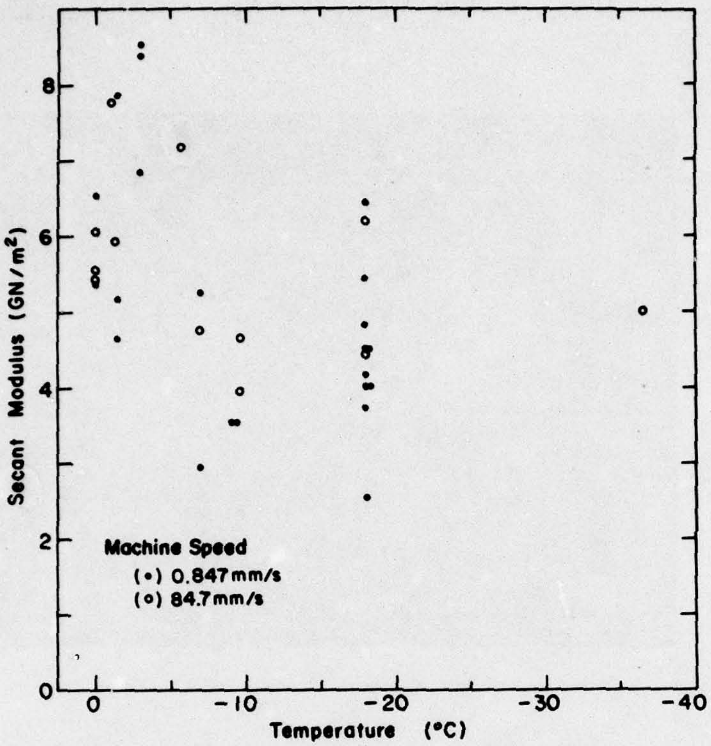


Figure 11. Secant modulus vs temperature for the tensile tests.

with increasing strain rate. Their initial tangent modulus values were between 6.2 MN/m^2 and 11.72 MN/m^2 for compression tests and between 4.27 MN/m^2 and 6.9 MN/m^2 for tension tests.

The initial tangent modulus values found in this study and given in Figure 9 show good agreement with Hawkes and Mellor (1972) at −7°C. At lower temperatures the values tended to increase, indicating a temperature effect. The 50% strength modulus shown in Figure 10 tends to increase slightly with temperature.

For the tension tests, the deformations were extremely small; therefore, only the secant modulus was found from the oscilloscope records and is shown in Figure 11. The data records indicate that the initial tangent modulus was slightly higher than the secant modulus. Very good agreement between the secant modulus and the initial tangent modulus reported by Hawkes and Mellor (1972) was found.

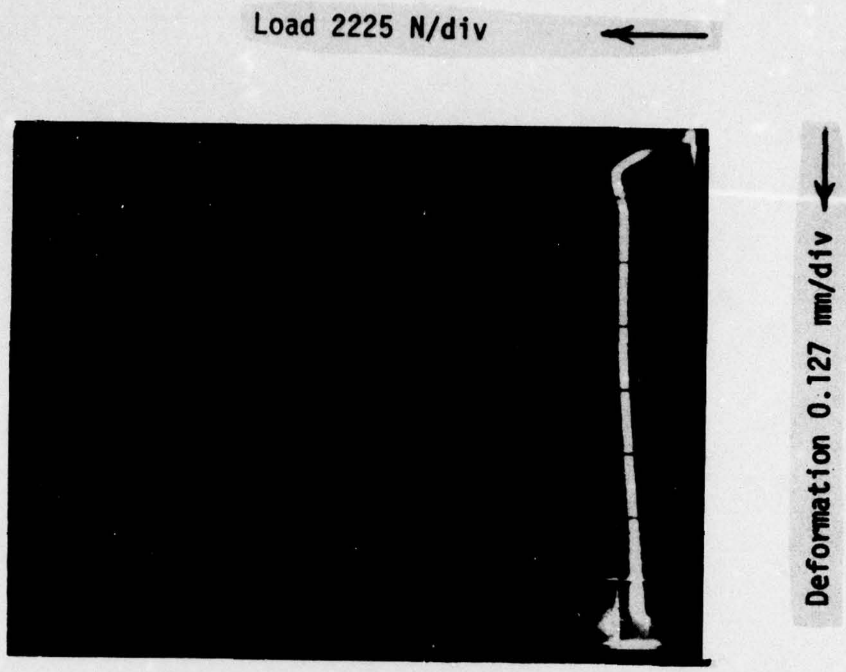
Mode of failure

Failure modes for uniaxial tests on ice and frozen soil are described by Hawkes and Mellor (1970, 1972). Carter (1970) discusses the brittle fracture of snow-ice. He proposed failure criteria for both tension and compression based on dislocation theory.

In this study the compression tests exhibited a ductile failure at −0.1°C with the slower machine speed of 0.847 mm/s as shown on the cover and in Figure 12. A combination of ductile yield and brittle fracture was observed at −17°C and a machine speed of 0.847 mm/s as shown in Figure 13. At a machine speed of 8.47 mm/s and a temperature of −54°C, brittle fracture occurred, as shown in Figure 14.

All tensile tests produced specimen failure by brittle fracture. A typical load-deformation curve and failure in the neck section is shown in Figure 15. Failure near the end of the neck section observed with the split end caps is shown in Figure 15. Irregular fracture planes (Fig. 14 and 15) are discussed by Hawkes and Mellor (1970). They explain this phenomenon by crack initiation and arrest at various locations on the ultimate failure surface. With increasing load the noncoplanar cracks coalesce to form an irregular fracture surface.

The ratio of compressive strength to tensile strength varies widely with temperature and strain rate; e.g. the ratio is about 2 to 1 at −0.1°C and about 10 to 1 at −36.5°C. The failure theory proposed by Griffith (1924) appears reasonable for the present results because of the bubbles present in the ice specimens. However, the present results do not agree with



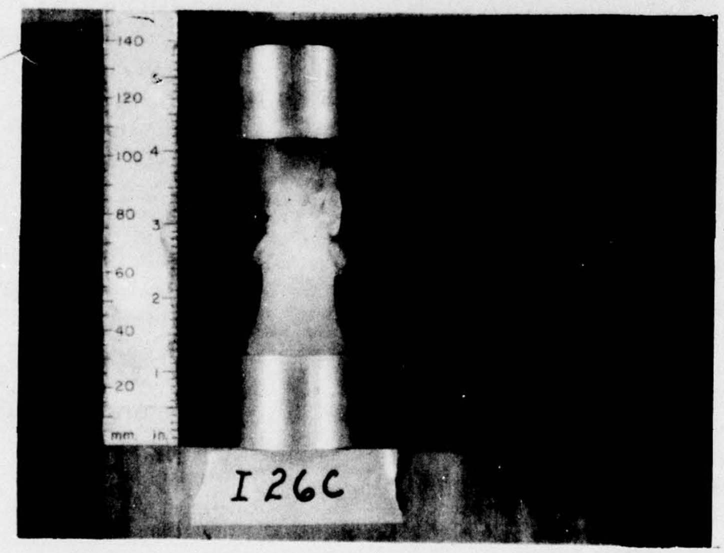


Figure 12. Compression test at −0.1°C with a machine speed of 0.847 mm/s.

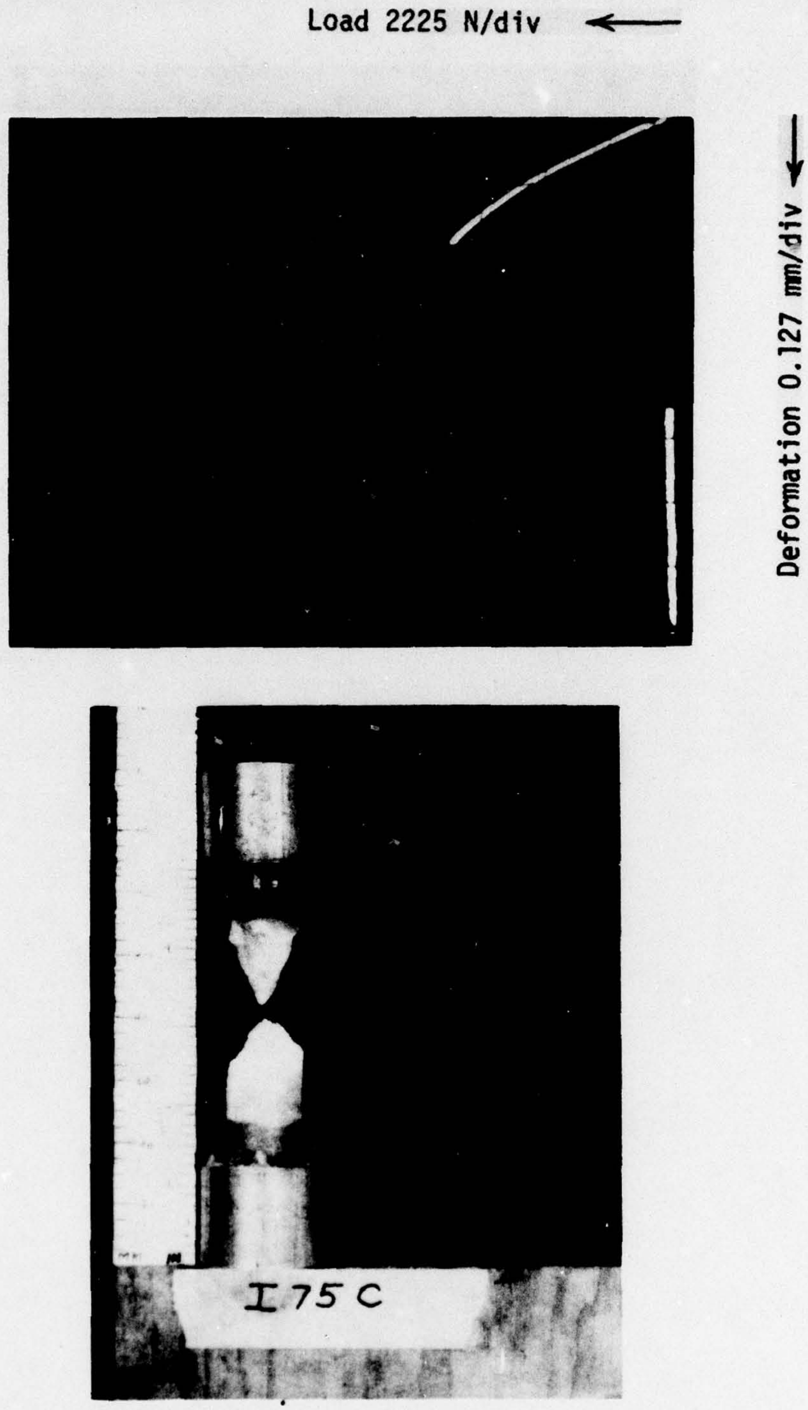
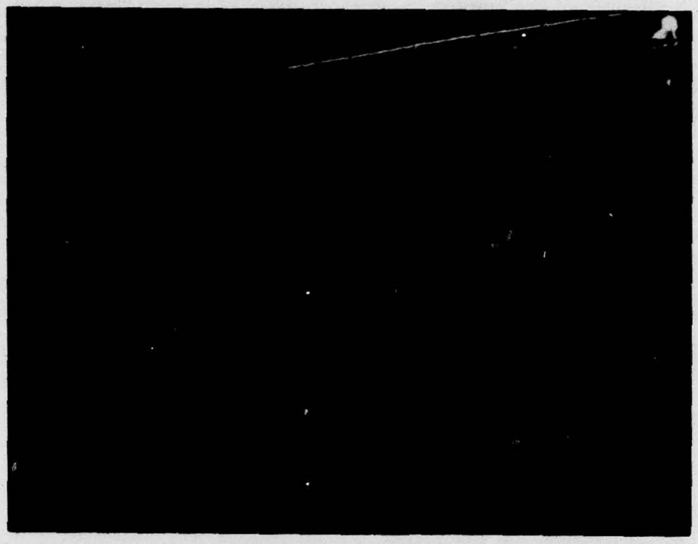


Figure 13. Compression test at −17°C with a machine speed of 0.847 mm/s.



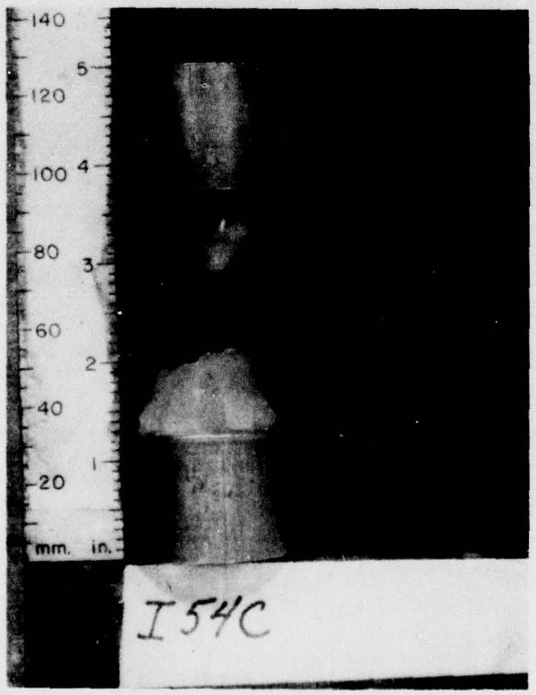
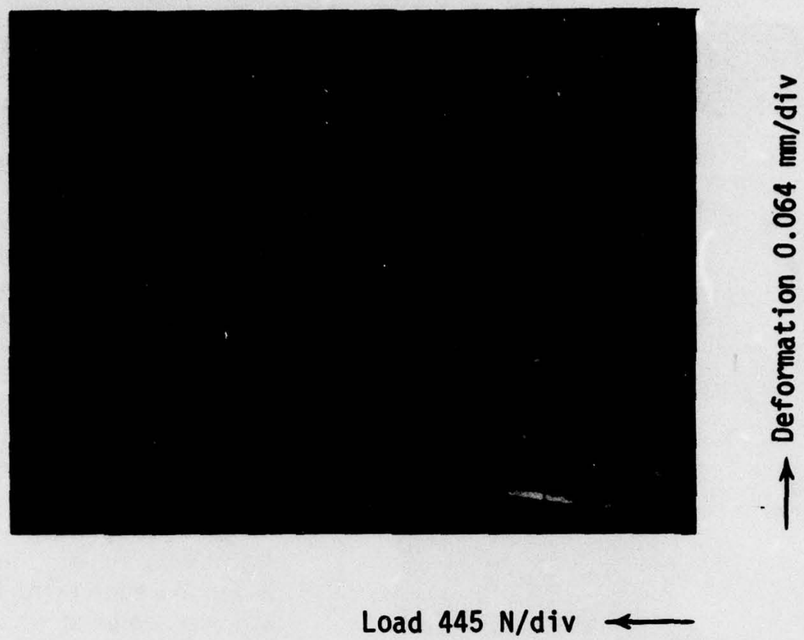


Figure 14. Compression test at −54°C with a machine speed of 84.7 mm/s.



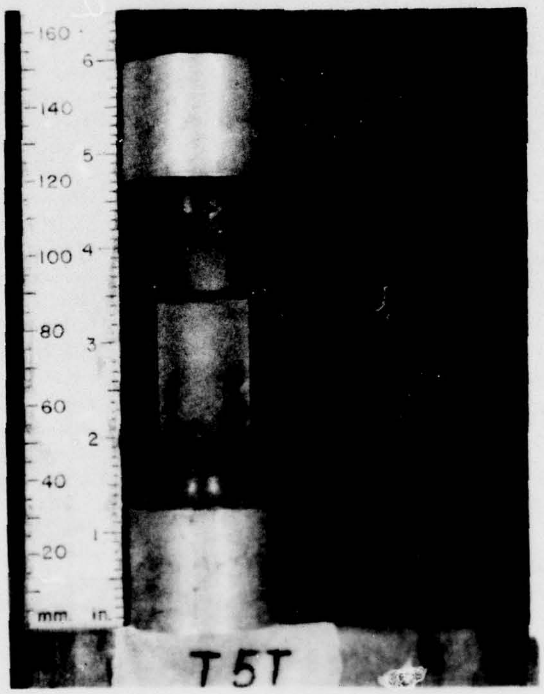


Figure 15. Tensile test at −3°C with a machine speed of 0.847 mm/s.

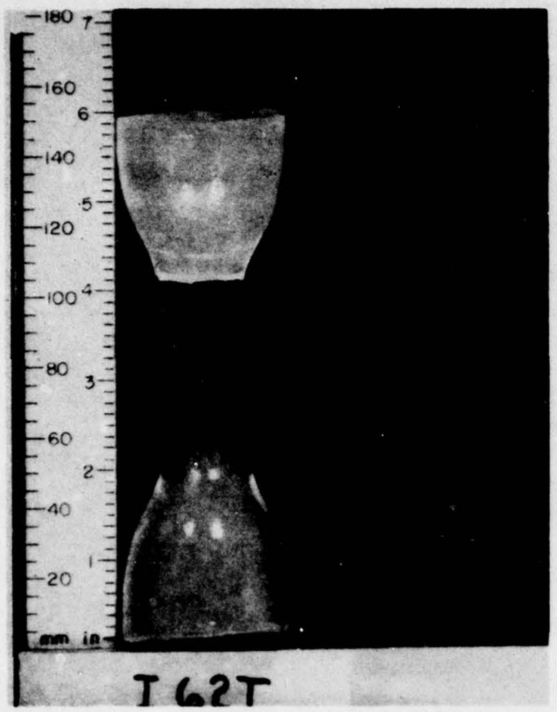


Figure 16. Tensile test with split end caps.

Griffith's assumption that the compressive strength of a brittle material is eight times the tensile strength.

CONCLUSIONS

The uniaxial compression tests conducted on polycrystalline ice in this study indicate that the strength is very sensitive to temperature. At strain rates of about 1.5×10^{-1} s^{-1} and 2.0×10^{-3} s^{-1}, the strength increased about one order of magnitude as the temperature decreased from -0.1°C to -54°C. The average rate of increase for the 1.5×10^{-1} s^{-1} tests was 0.78 MN/m^2 °C. For the 2.0×10^{-3} s^{-1} tests the average rate of increase was 0.6 MN/m^2 °C between $-3°$ and -35°C. The results indicate that the strength increased about 2½ times between -0.1°C and -3°C for the 2.0×10^{-3} s^{-1} tests. At comparable temperatures and loading rates, the compressive strength and rates of increase found in this study are higher than those found by other investigators. This may be partly due to the relatively stiff testing machine used in this investigation.

Valid tensile tests were difficult to obtain. Only 36 of the total 85 tests run were considered valid. Problems with slippage of the specimen in the gripping system and differential thermal contraction between the end caps and specimen are difficult to surmount. Valid test results indicate an increase in uniaxial tensile strength with temperature, especially between -0.1°C and -3°C. The results agree very well with other investigations.

The initial tangent modulus increased about two times as the temperature decreased from -0.1°C to -54°C. At comparable temperatures, the results agree well with a previous investigation. The 50% stress modulus also increased with decreasing temperature. A secant modulus found for the tensile tests agreed well with results from a previous investigation.

The results of this study provide data on material properties which are useful for establishing design criteria for structures subjected to ice forces. Additional testing is needed at lower temperatures and higher strain rates. Better techniques are required for uniaxial tensile testing of polycrystalline ice.

LITERATURE CITED

Butkovich, T.R. (1954) Hardness of single ice crystals. U.S. Snow, Ice and Permafrost Research Establishment Research Paper 9. AD 041580.

Butkovich, T.R. (1955) Crushing strength of lake ice. CRREL Research Report 15. AD 075249.

Carter, D. (1970) Brittle fracture of snow ice. *Proceedings, IAHR Symposium*, Reykjavik, Iceland, section 5.2.

Dykins, J.E. (1966) Ice engineering tensile and bending properties of sea ice grown in a confined system. U.S. Naval Civil Engineering Laboratory Technical Report R415.

Frankenstein, G.E. (1959) Strength data on lake ice. CRREL Technical Report 59. AD 236204.

Griffith, A.A. (1924) The theory of rupture. *Proceedings of the First International Congress for Applied Mechanics*, Delft, p. 55-63.

Hawkes, I. and M. Mellor (1970) Uniaxial testing in rock mechanics laboratories. *Engineering Geology*, vol. 4, no. 3, p. 217-218.

Hawkes, I. and M. Mellor (1972) Deformation and fracture of ice under uniaxial stress. *Journal of Glaciology*, vol. 11, no. 61, p. 103-131.

Haynes, F.D. (1973) Tensile strength of ice under triaxial stresses. CRREL Research Report 312. AD 774194.

Haynes, F.D., J.A. Karalius and J. Kalafut (1975) Strain rate effect on the strength of frozen silt. CRREL Research Report 350. AD 021981.

Kovacs, A., F. Michitti and J. Kalafut (1977) Unconfined compression tests on snow, a comparative study. CRREL Special Report 77-20.

Mellor, M. and J. Smith (1966) Strength studies of snow. CRREL Research Report 168. AD 631717.

Weeks, W.F. and A. Assur (1969) Fracture of lake and sea ice. CRREL Research Report 269. AD 697750.

Wolfe, L.H. and J.O. Thieme (1964) Physical and thermal properties of frozen soil and ice. *Journal of the Society of Petroleum Technology*, March, p. 67-72.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Haynes, F. Donald

Effect of temperature on the strength of snow-ice / by F. Donald Haynes. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1978.

iii, 22 p., illus.; 27 cm. (CRREL Report 78-27.)

Prepared for Directorate of Civil Works - Office, Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory, under CWIS 31332.

Bibliography: p. 18.

1. Snow-ice. 2. Strain rate. 3. Temperature effects. 4. Uniaxial compression tests. 5. Uniaxial tension tests. I. United States. Army. Corps of Engineers. II. Series: Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL Report 78-27.

END
5-87
DTIC